Report No. NA-70-23
(DS-70-2)

FINAL REPORT

Project No. 520-003-01X

ACCELERATED TESTING OF GENERAL AVIATION ENGINE EXHUAST SYSTEMS

FEBRUARY 1970

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
National Aviation Facilities Experimental Center
Atlantic City, New Jersey 08405

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Prepared by:
GERALD SLUSHER

for

AIRCRAFT DEVELOPMENT SERVICE

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DEPARTMENT OF TRANSPORTATION
Federal Aviation Administration
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INTRODUCTION

Purpose

The purpose of this project was to develop a qualification test and procedure suitable for evaluating the reliability and integrity of the exhaust systems of single-engine aircraft incorporating exhaust gas-to-air heat exchangers. A secondary purpose was the evaluation of an improved material for exhaust system applications.

Background

The Federal Aviation Administration (FAA) was engaged in a program concerned with the safety and reliability of engine exhaust systems in light aircraft. The program consisted of six basic phases: (1) a comprehensive study of the records of engine exhaust system failures that cause carbon monoxide, fire, and power loss hazards in general aviation aircraft, the results of which are presented in Reference 1; (2) a metallurgical analysis of failed exhaust system components from operating aircraft located throughout the contiguous United States, the results of which are reported in Reference 2; (3) an evaluation of low-cost carbon monoxide indicators to determine their performance and suitability for use in general aviation aircraft, and reported in Reference 3; (4) inflight and ground tests of typical exhaust system installations to obtain vibration and thermal information for use in establishing realistic design and test criteria, the results of which were published in Reference 4; (5) the phase reported herein which consisted of developing a ground test schedule and procedure for exhaust systems on engine stands and was carried out on several typical installations, and evaluated by comparison of the results of these tests with service experience in operational aircraft; and (6) a metallurgical evaluation of exhaust system components that failed during qualification testing to demonstrate correlation, or lack thereof, between failures in the test and in the field, the results of which are presented in Reference 5.

All exhaust system failures, regardless of location in general aviation aircraft of the single-engine type, are considered hazardous. Failures can result in three separate hazards to flight safety:
(1) fractures in the muffler outer wall (heat exchanger surface) may contaminate the cabin with exhaust gases containing carbon monoxide;
(2) failed muffler baffles may restrict the exhaust gas path and effect engine power loss by creating excessive exhaust back pressures; and
(3) when ruptured, the exhaust manifold or stacks may induce a fire hazard by failure to contain the exhaust flames.

This project was undertaken to provide a technical basis upon which more specific and detailed criteria can be established to guide the manufacture of general aviation exhaust systems and was directed toward the development of appropriate tests for new exhaust systems that could be utilized to facilitate development and assure system reliability.

Description of Aircraft and Engines: The project endeavor was concerned with single-engine, two-through-six place, general aviation aircraft incorporating exhaust gas-to-air heat exchangers. Aircraft powerplants used in the test program were four- or six-cylinder, horizontally-opposed, reciprocating engines ranging from 100 to 260 hp. Engine compression ratios varied from 6.75:1 to 8.6:1. The aircraft and engines were models manufactured in large quantities by two light-aircraft companies and two engine companies, respectively. Aircraft and engine specifications are listed in Table I.

TABLE I

AIRCRAFT AND ENGINE INFORMATION

Aircraft Code Model	Number of Places	Engine Rating (hp)	Number of Cylinders	Engine Displacement (cu. in.)	Engine Compression Ratio
A	4	250	6	540	8.5:1
B	6	260	6	470	8.6:1
C	4	180	4	360	8.5:1
D	4	145	6	300	7.0:1
E	2	100	4	200	7.0:1
F	2	108	4	235	6.75:1
G	4	180	4	360	8.5:1

Description of Exhaust Systems: The exhaust systems tested utilize the heat from engine exhaust gases in heating cabin air. Shrouds are wrapped around the muffler through which air is rammed for heating the cabin. When a failure occurs in the muffler outer wall, exhaust gases containing carbon monoxide may enter the cabin through the ventilating system.

The exhaust systems may be classified under two basic designs: (1) the crossover-type and (2) the separate-type. In the crossover-type, shown in Figure 1, the exhaust stacks from both banks of engine exhaust ports feed a single crossover muffler which forms an integral part of the system. The muffler is usually supported horizontally by the stacks and is located immediately behind the engine. As the name implies, the separate-type, shown in Figure 2, has a muffler and a tailpipe for each bank of cylinders with the muffler supported either vertically or at a downward angle.

Exhaust systems are currently fabricated from AISI-321 or AISI-347 stainless steels. These steels are austenitic by virtue of their high nickel content. The crystal structure of austenite is face centered cubic. These steels are nonmagnetic and are not heat treatable but can be cold worked to high strength and hardness. The materials are often referred to as 18-8 stainless steels having about 17 to 19 percent chromium and 8 to 13 percent nickel. They contain a maximum of 0.08 percent carbon and an average of 2.50 percent manganese. Susceptibility to intergranular corrosion is reduced by the addition of titanium or columbium. AISI Type 321 is stabilized by adding about 0.40 percent titanium; and Type 347 contains about 0.80 percent columbium. Tensile strength varies from 90,000 to 100,000 psi in the annealed state. Cold working will increase the tensile strength to a range of 120,000 to 125,000 psi. Elongation varies from 60 to 70 percent.

An exhaust system fabricated from a material consisting basically of 32 percent nickel, 46 percent iron, and 21 percent chromium was evaluated as an improvement over the standard materials in regard to resistance to high-temperature oxidation or corrosion and a combination of carburization and attack by the products of combustion, particularly lead compounds. The chromium in the alloy imparts resistance to oxidation and corrosion. The high percentage of nickel keeps the structure austenitic so that the alloy is ductile. It also contributes resistance to scaling, general corrosion, and to stress corrosion cracking. The iron content aids in resistance to sulfur attack and "green rot" or internal oxidation.

The alloy is readily fabricated and welded by standard commercial procedures. Because of its stable austenitic structure, it does not form the brittle "sigma" phase even after long periods of use in the critical temperature range of 1200°F to 1600°F.

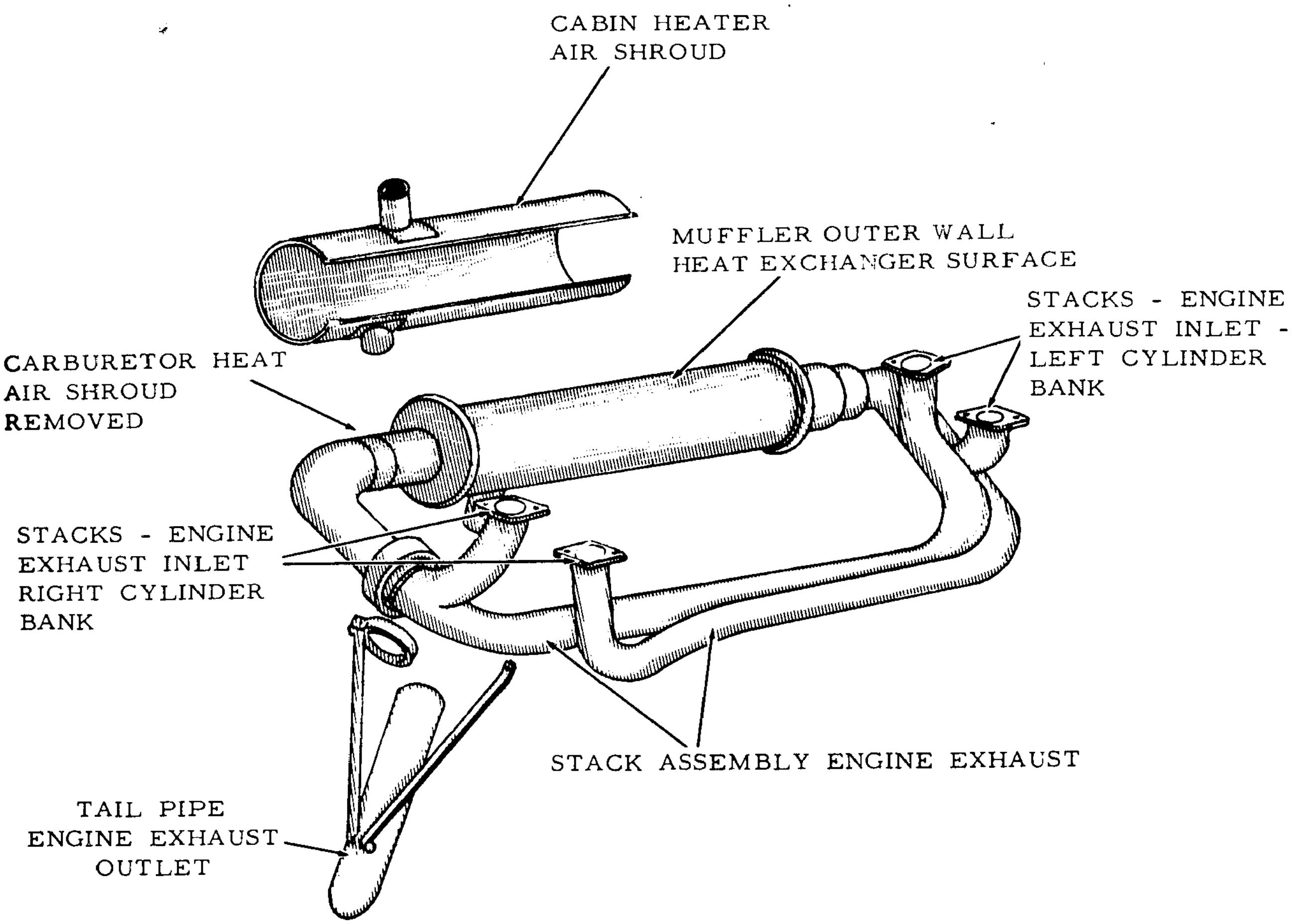

FIG. 1 TYPICAL CROSSOVER TYPE EXHAUST SYSTEM

It is also anticipated that the material will be a significant improvement over AISI-321 and AISI-347 stainless steels in regard to stress-corrosion cracking. The fatigue strength, however, is not improved and is comparable to that of the standard materials.

DISCUSSION

Test Procedures

Although the qualification tests were developed on engine stands, testing was initiated by flight tests with five typical aircraft to obtain environmental operating information with which to make the ground tests realistic. The vibration and temperature levels of the engines and exhaust systems were measured on aircraft in flight and then on the ground on engine stands. The instrumentation for both types of testing was identical. This information is contained in a previous report, Reference 4.

Testing was accomplished on each of seven engine installations mounted on stands in a manner designed to produce a realistic environment as defined from in-flight information. The test installations incorporated aircraft parts forward of the firewall as depicted in Figure 3. To reproduce conditions of aircraft vibrations, the engines were mounted on the aircraft vibration isolators and supported in cantilevered fashion from the firewall with the standard aircraft engine mount assembly. Engine power was absorbed by two-blade propellers as utilized in flight.

Engine and exhaust system temperature levels were reproduced by utilizing standard aircraft cowling and baffles, with the exception that the top cowling was modified for incorporation of air scoops, to provide additional engine-cooling air representative of in-flight conditions. Large oil coolers were placed in the propeller slipstream for cooling the engine oil as required for running the engines at maximum power on the ground.

The heated air from the exhaust heaters was routed into cabin simulator chambers where the carbon monoxide concentration was continuously sampled and measured. Upon obtaining a positive carbon monoxide measurement, an inspection and investigation were conducted to determine the source of contamination. A description of the facility and instrumentation utilized in carbon monoxide measurements is provided in a previously published report, Reference 3. An inspection of the exterior and interior of the exhaust system, using a light and mirrors through the tailpipe, was performed after each engine shutdown. Following test periods of 25 hours, the exhaust systems were disassembled, inspected, and pressure tested under water to reveal the presence of hidden or invisible cracks or fractures in the heat exchanger surface.

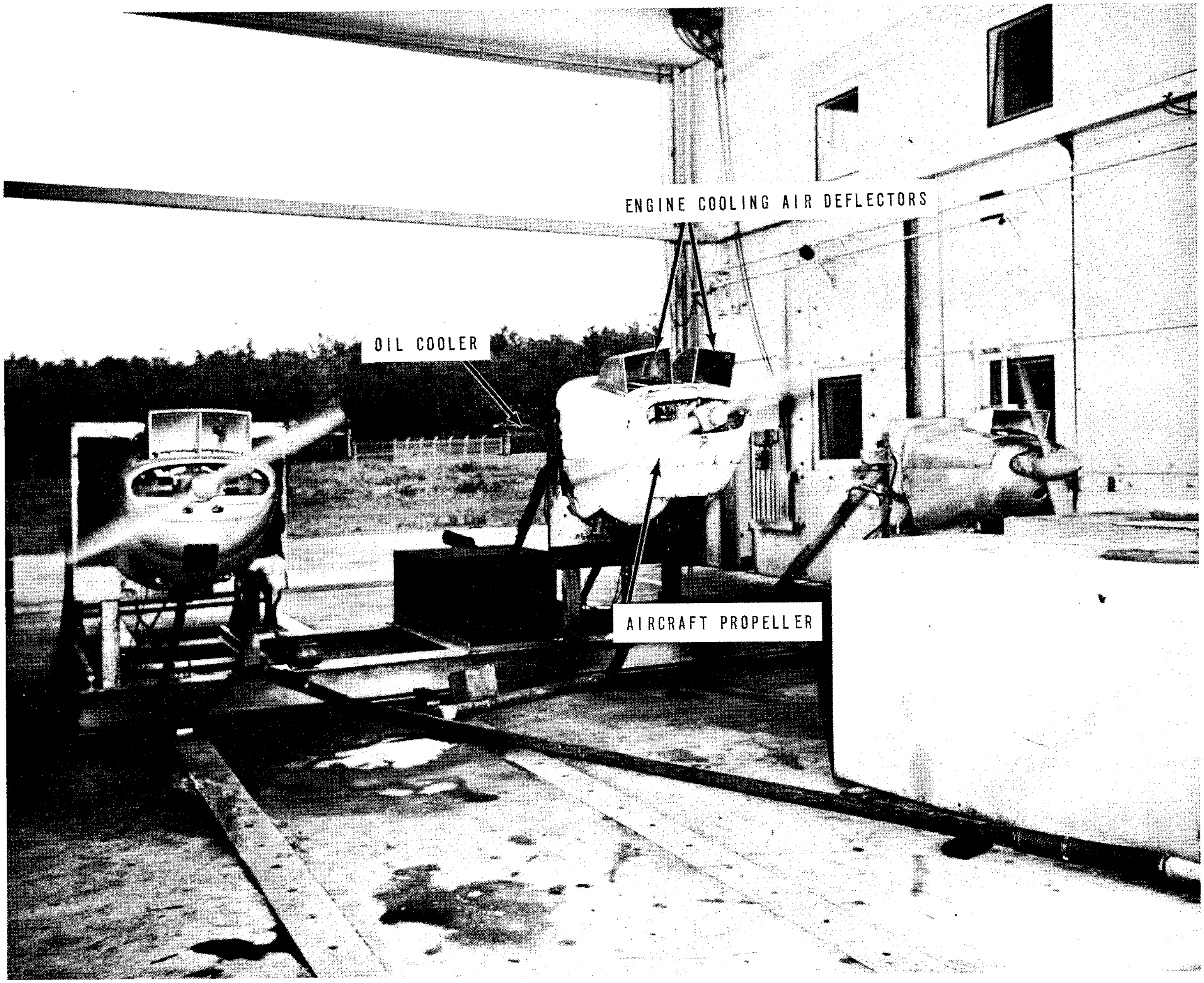

FIG. 3 ENGINE STANDS

Development of Test Schedule

The objective of a qualification test schedule was to produce realistic exhaust system failures in less operating time than that required for the same failure to occur in operating aircraft. In the establishment of an applicable schedule, the factors affecting failure were examined for assuring that the schedule would produce appropriate extreme conditions and thereby accelerate failure. The factors reported in References 2 and 5 are of three types: (1) fatigue attributed to excessive vibrational and thermal cyclic stresses at locations of abrupt changes in section size, (2) severe high-temperature oxidation occurring in areas of overheating resulting from a combination of high-temperature carburization and attack by the products of combustion, particularly lead compounds, and (3) corrosion fatigue produced by a combination of items (1) and (2) above. The conditions for fatigue, abrupt changes in section size, and weakening by thinning, occur over a period of time by high-temperature oxidation which penetrates the surface in an irregular manner producing notches and locations of high-stress concentration. High cyclic stresses are produced by conditions of maximum vibration and particularly extreme changes in metal temperature. Corrosion or temperature oxidation is accelerated under conditions of high exhaust temperature levels when accompanied by mechanical flexing and scaling produced by cyclic thermal condition.

Analysis of the in-flight data, Reference 4, shows that extremes in both vibration and exhaust temperature occur under conditions of maximum power. An accelerated test schedule would then require significant operating time under conditions of maximum engine power. Thermal shock (extremes in cyclic thermal stresses and scaling), however, is known to be a significant factor affecting failures. The test schedule must incorporate cycling between (minimum and maximum temperatures) idle and maximum power. As resonance vibration conditions may occur anywhere within the aircraft engine operating power requirements, the test schedule must specify operation throughout the power requirements. A problem of serious magnitude is the weighing or proportioning of test time under each of the conditions discussed since the qualification test must produce all types of failures in their proper proportion.

The engine power settings specified by FAA for engine certification were selected with the exception of the idle power setting which was added to facilitate thermal cycling. A 5-hour running schedule was established similar to the schedule required for turbine engines. The power settings were varied at least once each 15-minute period and in many cases after periods of 5 and 10 minutes. The time at each power setting was proportioned in the 5-hour cycle so that the accumulated time at each power condition after 150 hours would approximate that required by the FAA engine block tests. The engine test schedule utilized for all tests reported herein is contained in Table II.

TABLE II

EXHAUST SYSTEM TEST SCHEDULE

1. One hour of alternate periods of:

    a. Five minutes at maximum power.
    b. One-minute deceleration to idle.
    c. Three minutes at idle.
    d. One-minute acceleration to maximum power.

2. One-engine backfire at magneto test speed.

3. Forty minutes of alternate periods of:

    a. Fifteen minutes at maximum power.
    b. Five minutes at 75 percent maximum continuous power.

4. Forty minutes of alternate periods of:

    a. Fifteen minutes at maximum power.
    b. Five minutes at 70 percent maximum continuous power.

5. Forty minutes of alternate periods of:

    a. Fifteen minutes at maximum power.
    b. Five minutes at 65 percent maximum continuous power.

6. Forty minutes of alternate periods of:

    a. Fifteen minutes at maximum power.
    b. Five minutes at 60 percent maximum continuous power.

7. Forty minutes of alternate periods of:

    a. Fifteen minutes at maximum power.
    b. Five minutes at 50 percent maximum continuous power.

8. Forty minutes of alternate periods of:

    a. Ten minutes at maximum power.
    b. Ten minutes at best economy cruising power.

9. One-hour engine shutdown.

Seven standard exhaust systems and one system fabricated of an improved material were tested in accordance with the test schedule and procedure until either failure occurred or 600 hours were accumulated. The program resulted in the accumulation of 3,643 total test hours.

Results

The malfunctions and defects occurring in the exhaust systems during the tests are listed in Table III. Also tabulated are the aircraft code letter, the number of test hours, and the figure number depicting the failure. The failures are discussed and analyzed in the Appendix. The results with the exhaust system fabricated of a more corrosion-resistant material are included.

The standard systems of Aircraft Code Models D and F and the system fabricated of a more corrosion-resistant material were tested for 600 hours without failure. This result with the two standard systems was attributed to the moderate vibration and temperature environment produced by the engines of low-power rating (108 and 145 hp) and low-compression ratios (6.75:1 and 7.0:1).

Analysis of Results

Test Acceleration Factor: The exhaust systems tested were models that had been developed and improved by the manufacturers through design changes as proved necessary by failures occurring in aircraft. A test procedure established by testing and effecting realistic failures in the developed systems should be effective for evaluation and development of new designs.

The service records over the time period of 1962 through 1967 were reviewed for the purpose of comparing failures in aircraft with the failures produced by conducting tests. This study was undertaken to:

1. Determine if the test failures were similar to those occurring in operating aircraft.

2. Calculate a test acceleration factor.

The number of failures resulting from tests and from service and the times for failure are listed in Table IV. Included is a calculated test severity factor.

In operating aircraft, failure of the baffle tube in the mufflers of Aircraft Code Models A and G occurred at an average operating time of 653 hours as calculated from sample size of 109. This indicates that the two baffle tube failures occurring during test were representative of failures occurring in aircraft.

TABLE III

SUMMARY - EXHAUST SYSTEM TEST FAILURES

Aircraft Code Model	Test Hours to Failure	Description	Figure No. *
G	43	Baffle Tube, Muffler	1.1
G	43	End Plates, Muffler	1.2
B	112	Joint, Stack Right Center	1.3
B	140	Joint, Stack Right Center	1.3
C	150	Shroud, Carburetor Heat	1.4
A	160	Baffle Tube, Muffler	1.5
C, D, E	305 346 400 525	Gasket, Exhaust Flange	1.6
B	440	Diffuser Cone, Muffler	1.7
C	448	End Plate, Muffler	1.8
C	490	Baffle Tube Rivets, Muffler	1.9
C	490	Joint, Manifold-to-Muffler	1.10, 1.11
E	550	Heat Exchanger, Muffler Wall	1.12

* Appendix

TABLE IV

COMPARISON OF TEST FAILURES WITH AIRCRAFT FAILURES

Aircraft Code Model	Description	TEST FAILURES No. of Failures	TEST FAILURES Avg. No. Of Hours	AIRCRAFT FAILURES No. of Failures	AIRCRAFT FAILURES Avg. No. Of Hours	Sigma σ	Test Acceleration Factor
A & G	Baffle Tube, Muffler	2	101	109	653	248	6.4
G	End Plates, Muffler	2	43	21	496	355	11.5
B	Stack, Right Center	2	126	1	380		3.0
C	Shroud, Carburetor Heat	1	150	3	299		2.0
B	Diffuser Cone, Muffler	1	440	9	918	210	2.1
C	Baffle Tube, Muffler	1	490	30	1209	424	2.5
C	Joint, Manifold-to-Muffler	1	490	5	469		1.0
E	Heat Exchanger, Muffler Wall	1	550	61	1132	602	2.0
			TOTAL -	239		AVERAGE -	3.8

The test acceleration factor was calculated from the ratio of number of hours for failure in aircraft to the number of hours for failure during test. For the baffle tube failure a test acceleration factor of over 6 was indicated.

Twenty-one failures of the muffler end plate occurred in Aircraft Code Model G at a mean operational time of 496 hours. The failure of both muffler end plates occurred during test at 43 test hours which indicates a test acceleration factor of 11.5.

The carburetor heat air shroud, Aircraft Code Model C, failed during test at 150 hours. Three similar failures occurred in aircraft at a mean operational time of 299 hours. A test acceleration factor of 2 was indicated.

Nine diffuser cones within the mufflers of operational Aircraft Code Model B failed at a mean operating time of 918 hours. The test failure occurred at 440 hours which indicates a test acceleration factor of 2.1.

The service records document 30 baffle tube failures occurring at an average operating time of 1,204 hours in Aircraft Code Model C. As the one test failure occurred at 490 hours, a test acceleration of 2.5 was indicated.

Failure of the manifold-to-muffler joint occurred at a mean time of 469 hours in operational Aircraft Code Model C. The one test failure occurred at 490 test hours indicating a test acceleration factor of 1.0.

Sixty-one failures of the muffler wall (heat exchanger surface) that could permit carbon monoxide to enter the cabin occurred in operational Aircraft Code Model E at a mean time of 1,132 hours. The test failure occurred at 550 hours indicating a test acceleration factor of 2.0.

With one exception, failures very similar to those that occurred during the accelerated tests have occurred in operational aircraft. The exception was the development of a crack along the radius in the muffler end plate of Aircraft Code Model C in the accelerated test; whereas, in aircraft the crack occurred along the circumference. However, as a total of at least 239 failures did occur in operational aircraft and they were similar to eight of the test failures, it was concluded that the proposed test schedule and procedure produced realistic failures. Further, by performing metallurgical analysis, it was concluded in Reference 5, "In general, the types of failures experienced on the test stand samples were similar to those experienced on the corresponding operating aircraft samples as reported in Reference 2."

The test acceleration factor was indicated to be within a range from 1.0 to 11.5; however, five of the eight figures were between 2.0 and 3.0. The average test acceleration factor was 3.8 hours for failure in operational aircraft to 1 hour to produce a similar test failure. This result could be slightly higher than the actual factor because in a few cases the total aircraft operating time may have been reported as the exhaust system failure time, when the system may have been replaced. The acceleration factor may well be different for each type of failure.

Carbon Monoxide Contamination

During the testing, seven incidents occurred involving carbon monoxide entry into the heater and then into the simulated cabin. Exhaust gases entered existing openings under the cabin heater air shroud and passed into the cabin through the ventilating air system (refer to Figures 1.2, 1.5, 1.6, 1.8, and 1.10 in the Appendix). Failure of the manifold-to-muffler joint, Figure 1.10, permitted exhaust gases to impinge upon the muffler end plate and gases were blasted through existing openings under the cabin heater air shroud effecting a hazardous carbon monoxide concentration of .065 percent in the cabin simulator chamber. Failure of the muffler end plates, Figure 1.2, resulted in exiting exhaust gases entering existing openings under the cabin heater air shroud and contaminating the cabin air with .010 percent carbon monoxide. In four cases, gases escaping through blown exhaust flange gaskets entered the openings under the cabin heater air shroud and contaminated the cabin air with up to .0025 percent carbon monoxide. In two of the four incidents, the mufflers were fabricated with existing openings under the air shroud; and in two cases, the aluminum retaining parts melted and failed to maintain the seal of fiberglas packing resulting in openings under the cabin heater air shroud. Exhaust gases leaking through failed exhaust gaskets are usually diluted with engine cooling air and may seep into the cabin at concentrations less than .005 percent considered hazardous by the FAA. A second serious source of carbon monoxide contamination occurred upon the development of a crack in the heat exchanger surface permitting exhaust gases (.016 percent CO) from inside the muffler to enter directly into the heater, Figure 1.12. Although only one incident of this type occurred during test, this malfunction is a common hazard in aircraft of the type incorporating exhaust gas-to-air heat exchangers.

Design Features for Minimizing Hazards

Test results on the two basic exhaust system design configurations were separated and analyzed to determine the failure characteristics of one design in relation to the other. Results of testing the horizontal crossover-type exhaust systems are listed in Table V, and results of testing the separate-type exhaust systems are tabulated in Table VI.

TABLE V

FAILURES - HORIZONTAL CROSSOVER-TYPE EXHAUST SYSTEM

Aircraft Code Letter	No. of Test Hours Per Failure	Description	No. of Test Hours Per Aircraft
G	43	Baffle Tube, Muffler	
G	43	End Plates, Muffler	43
C	150	Shroud, Carburetor Heat	
C	448	End Plate, Muffler	
C	490	Baffle Tube Rivets, Muffler	
C	490	Joint, Manifold-to-Muffler	490
A	160	Baffle Tube, Muffler	160
F	___	No Failure	600
		TOTAL TEST HOURS	1293

TABLE VI

FAILURES - SEPARATE-TYPE EXHAUST SYSTEM

Aircraft Code Letter	No. of Test Hours Per Failure	Description	No. of Test Hours Per Aircraft
B	112	Joint, Stack Right Center	
B	140	Joint, Stack Right Center	
B	440	Diffuser Cone, Muffler	600
E	550	Heat Exchanger, Muffler Wall	550
D	___	No Failure	600
		TOTAL TEST HOURS	1750

Seven failures were experienced during a total of 1,293 test hours on the crossover-type exhaust systems for a rate of 185 test hours per failure. Four failures occurred during 1,750 test hours on the separate-type exhaust systems for a rate of 437 hours per failure. All but one of the failures in the crossover-type exhaust systems involved the muffler, and three of the seven failures involved the baffle tube within the muffler. The relatively low number of test hours (185 compared with 437) to effect failure in the crossover systems was attributed basically to the lesser material thickness (.020 inch) used in the crossover-type systems compared to that (.030 to .050 inch) used in the separate-type systems. If the material thickness was increased in the crossover-type muffler, the weight of the muffler would be increased and possibly result in a more severe cantilevered vibration problem. The relatively complicated crossover-type system could also be affected to a greater extent by unequal metal expansion when exposed to high-temperature gases. Because of these factors, the relatively simple separate-type exhaust systems appeared to be more durable, particularly when they are fabricated of corrosion-resistant material of .050 inch thickness.

An additional advantage of a separate-type exhaust system may exist upon failure of a baffle or diffuser cone within the muffler which could affect only one-half of the engine cylinders and partial engine power might possibly remain available. A similar failure in a crossover-type exhaust system could cause complete power failure.

The results discussed in the foregoing sections of this report demonstrate that cabin heaters and ventilating systems must be designed and constructed airtight to prevent concentrated gases from the nacelle area from entering the cabin. Quality control measures should include a pressure test of the ventilating system, particularly the area under the muffler air shroud.

Cracks in the heat exchanger surface invariably occur in proximity to the stack inlet or tailpipe outlet attachments in areas of stress concentration. The carbon monoxide hazard could be reduced by excluding the areas of stress concentration from the heat exchanger surface. A recommended heat exchanger design, to minimize stress concentration in the heat exchanger, would incorporate an axial flow through muffler with the manifold inlet attached to one end plate and the tailpipe outlet attached to the opposite end plate as shown in Figure 4. The heater would be configured with an air shroud wrapped around the outer cylinder surface. A perforated cone welded to the end plate, at the tailpipe outlet location inside the muffler as shown in Figure 4, is suggested to prevent broken fragments from sealing off the exit area in the event of a failure. The muffler would be fabricated of a more corrosion-resistant alloy consisting of 32 percent nickel, 46 percent iron, and 21 percent chromium in material thickness of .050 inch.

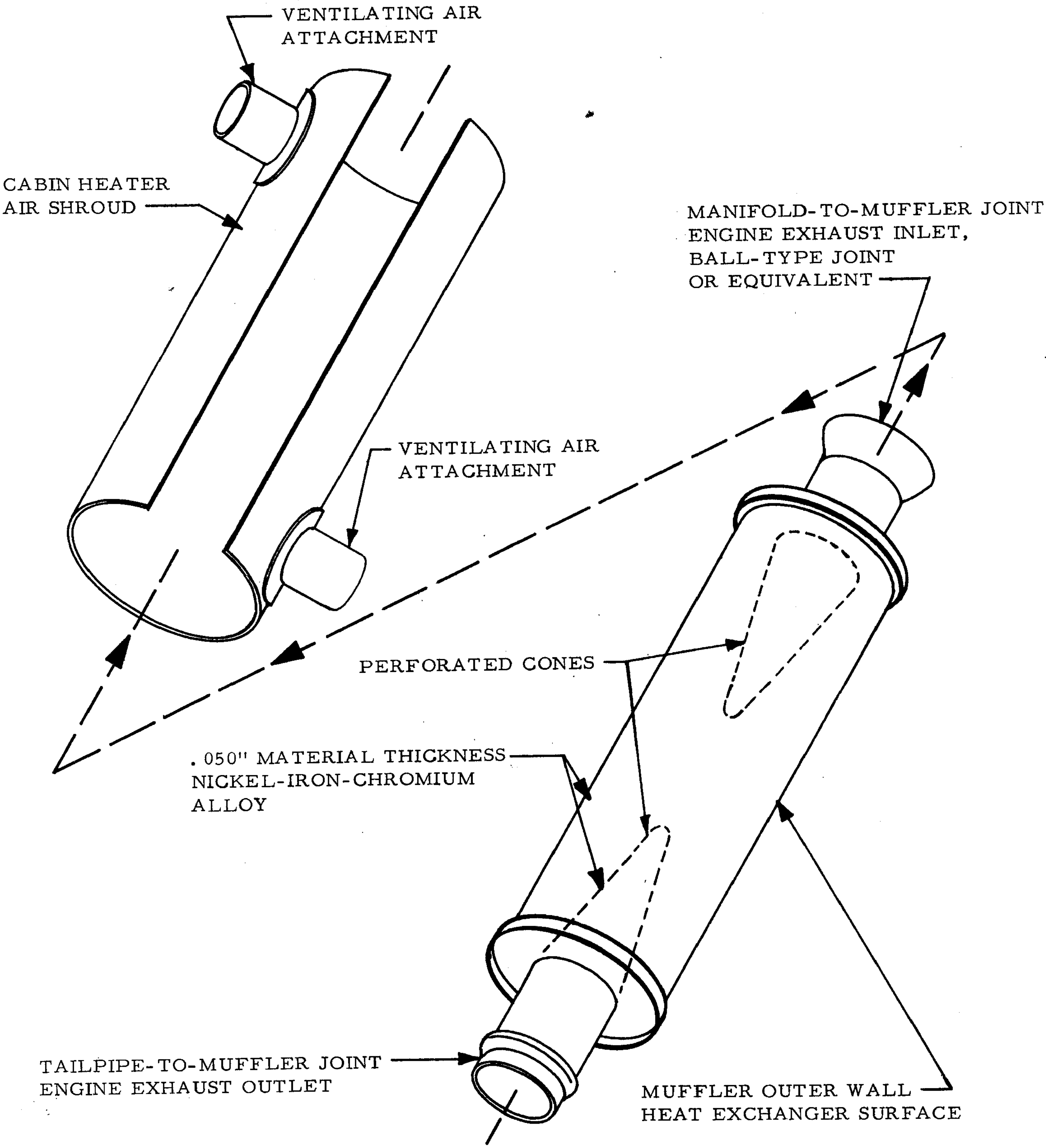

FIG. 4 RECOMMENDED MUFFLER AND HEAT EXCHANGER DESIGN

CONCLUSIONS

Based upon the results of the tests reported herein, it is concluded that:

1. The proposed test schedule and procedure established for exhaust systems produce metal deterioration and failures similar to those occurring in service as determined by direct comparison both visually and metallurgically.

2. One hour of testing exhaust systems in accordance with the proposed test schedule and procedure is equivalent to an average of 3.8 hours of aircraft operation.

3. Failures of exhaust components in addition to the exhaust heat exchanger can effect carbon monoxide contamination of the cabin air if openings exist in the cabin ventilating air system.

4. Separate-type exhaust systems are, in general, more durable than the horizontal crossover-type. The reduced material thickness coupled with other factors such as vibration and heat expansion, inherent in the horizontal crossover-type exhaust system, adversely affect its durability.

5. The utilization of a more corrosion-resistant material such as a nickel-iron-chromium alloy in exhaust system applications would significantly reduce or eliminate those failures resulting from high-temperature oxidation.

6. Failures effecting carbon monoxide and engine power loss hazards can be significantly reduced by constructing airtight exhaust heater ventilating systems and incorporating muffler designs of the axial flow-through type of a more corrosion-resistant material .050 inch thick.

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APPENDIX

EXHAUST SYSTEM MALFUNCTIONS AND DEFECTS

A detailed description and analysis of the exhaust system failures occurring as a result of testing is provided. The defects discussed in this section are tabulated in Table III, on Page 11 of this report. For purposes of analysis, failures are categorized according to the time of failure.

Test Hours - 43: A muffler baffle tube and both muffler end plates failed at only 43 test hours as shown in Figures 1.1 and 1.2. A section from the floating end of the tube separated into pieces and passed through the tailpipe. In this instance, the fragments did not lodge in the muffler or tailpipe and restrict the exhaust gas flow and effect an engine power loss as often accompanies this malfunction in aircraft.

Metallurgical analysis of the baffle tube failure is discussed under the subheading of Sample No. 1, and the failure is shown in Figures 1, 2, 3, and 4 of Reference 5 in this report. As stated, "The entire sample was heavily oxidized and somewhat distorted. The end at which the failure occurred was severly oxidized and eroded." The part was fabricated from AISI 347 stainless steel .020 inch thick. High-temperature oxidation occurring on both sides weakened the baffle tube effecting a failure at low test time. Information in Reference 4 indicates that this part operates under temperature levels of 1500°F to 1600°F maximum. Numerous similar failures have occurred in operating aircraft.

Failure of the end plates of the muffler is discussed under the subheadings of Samples Nos. 2 and 3, and depicted in Figures 5 through 13 of Reference 5. There was not an apparent metallurgical cause for failure noted. The most likely cause was believed to be high stresses induced by high-intensity vibration occurring after the baffle tube failure. Upon failure, the remaining portion of the tube was no longer supported from the floating end. A 19-inch section of the tube was then cantilevered from the end plate of the muffler effecting a severe vibration problem and high stresses.

A carbon monoxide hazard was effected by failure of the muffler end plates. Exhaust gases containing carbon monoxide exited through the fracture in the end plates and entered the cabin heater through the existing openings under the cabin heater air shroud and contaminated the cabin air with .010 percent carbon monoxide.

Test Hours - 112 and 140: Two similar cracks occurred in the stack joints as shown in Figure 1.3. The failed stack was replaced with an identical unit which also failed. The crack occurred in the swaged ferrule utilized for clamping and locking the joint and extended out

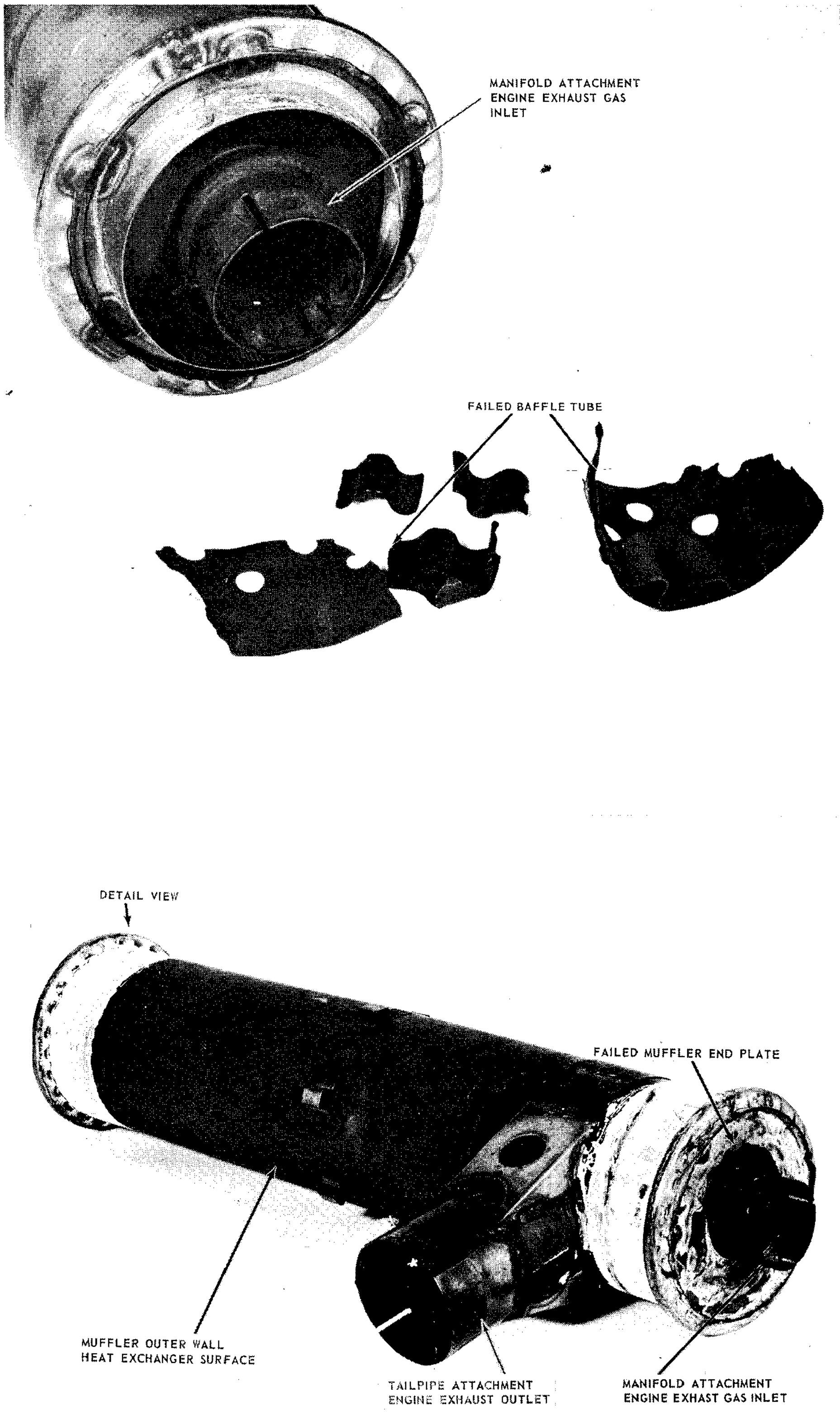
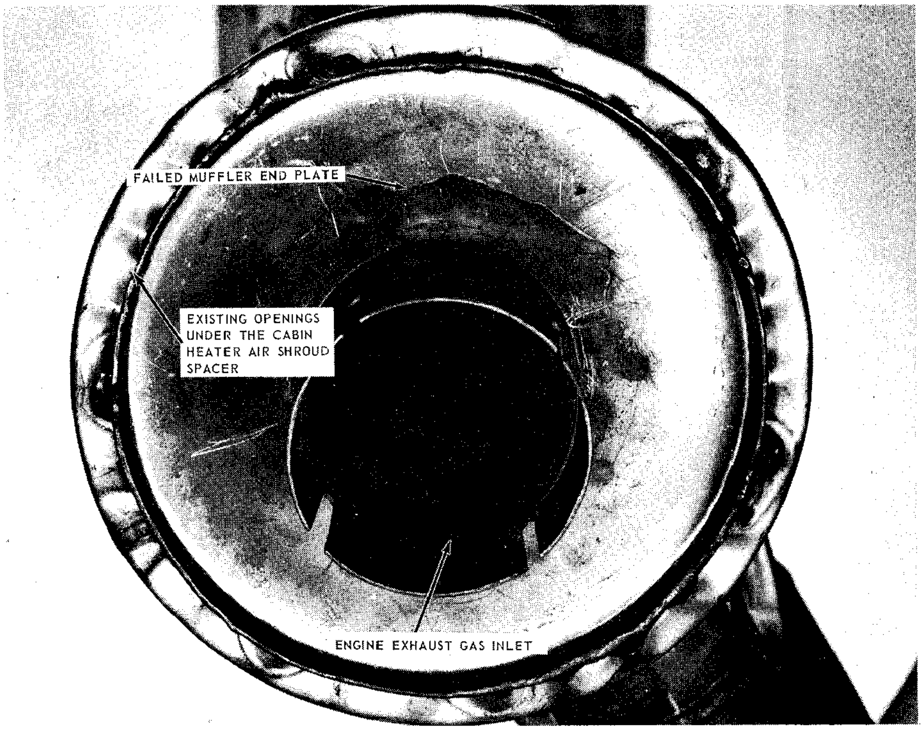


FIG. 1.1 FAILED MUFFLER BAFFLE TUBE AND END PLATES



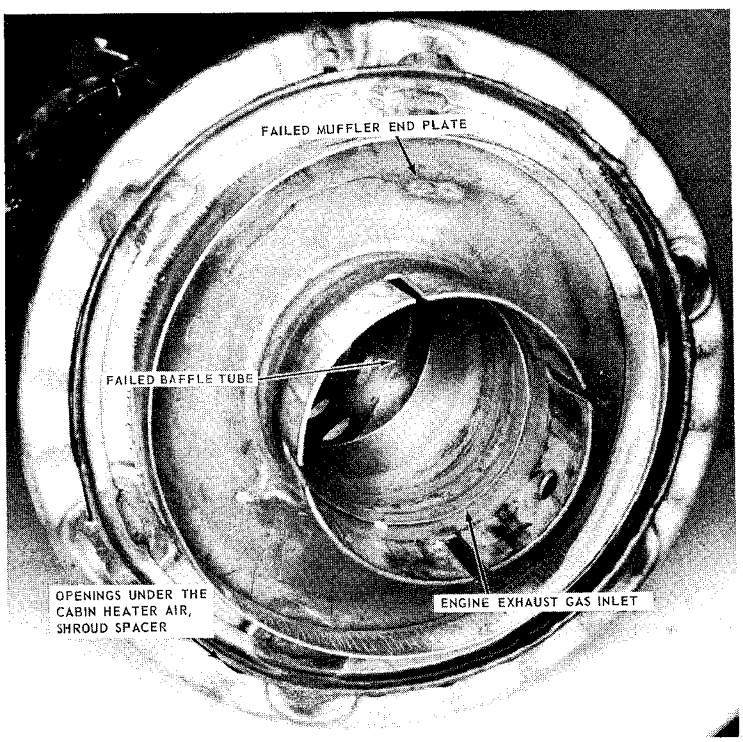


FIG. 1.2 FAILED MUFFLER END PLATES AND BAFFLE TUBE

FIG. 1.3 FAILED STACK JOINT

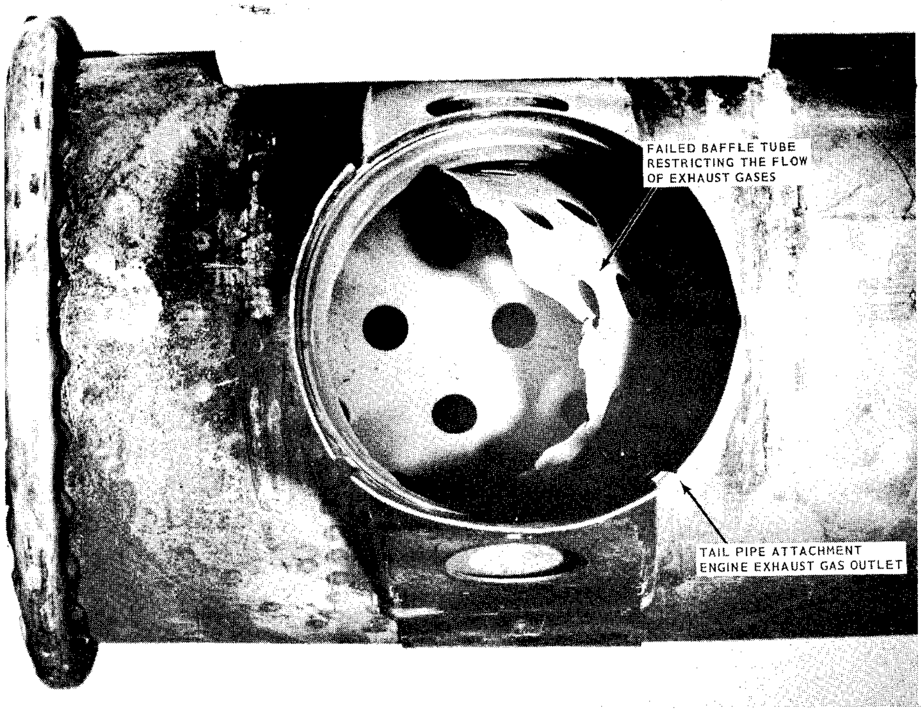
through the welded seam of the pipe. Metallurgical evaluation of the defect is discussed under the subheading of Sample No. 8, and the failure is presented in Figures 29 through 33 of Reference 5. As stated, "The Metallographic examination of the cross section of the crack revealed heavy oxidation on the surfaces on either side of the crack. This is a strong indication of the progressive nature of the crack since oxidation occurred on the fracture surface as the crack progressed. The fact that there is no thinning of the metal at the fracture also suggests that it is a type of fatigue crack. Slip bands are typical of a condition created at the tip of a fatigue crack."

After the second failure occurred, the manufacturer submitted a stack incorporating a modified joint which accumulated 350 test hours without failure. This part was fabricated from AISI 321 stainless steel .050 inch thick and operates at metal temperature levels up to 1200°F. (See Reference 4.)

Test Hours - 150: One end of a carburetor heat air shroud shattered at 150 test hours as shown in Figure 1.4. This part was fabricated from aluminum except the support end plates which were steel. The aluminum failed from fatigue which was believed to be aggravated by high temperatures. A number of similar failures have occurred in operating aircraft.

Test Hours - 160: A muffler baffle tube failed at 160 test hours effecting an engine power loss. A section of the baffle lodged in the muffler tailpipe outlet restricting the flow of exhaust gases as shown in Figure 1.5. Metallographic examination of this failure is analyzed under subheadings, Samples Nos. 4 and 5, and the failure is shown in Figures 14 through 19 of Reference 5. As stated, "The baffle exhibited severe oxidation and distorted edges at the failed area." This part was also fabricated from AISI 347 stainless steel material stock .020 inch thick. The basic failure was identical to the one occurring at 43 test hours discussed previously in this report. The baffle tube operates under maximum temperature levels of 1500°F to 1600°F. (See Reference 4.)

Test Hours - 305, 346, 400, and 525: The exhaust gaskets burned through at the above listed test hours as shown in Figure 1.6. Gasket failures permitted exhaust gases to contaminate the engine nacelle and resulted in seepage into the cabin through openings in the heater ventilating air system. In two incidents, the aluminum retaining parts melted and failed to retain the seal composed of fiberglas. Exhaust gases exiting through the blown gaskets entered the heater seal openings and contaminated the cabin air with .0025 percent carbon monoxide. Also, two cases of blown exhaust gaskets resulted in traces of carbon monoxide in the cabin air when exhaust gases entered existing openings under the cabin heater air shroud. Exhaust gas from blown gaskets is diluted with cooling air in the nacelle and usually seeps into the cabin at concentrations less than the limit of .005 percent considered hazardous by the Federal Aviation Administration.



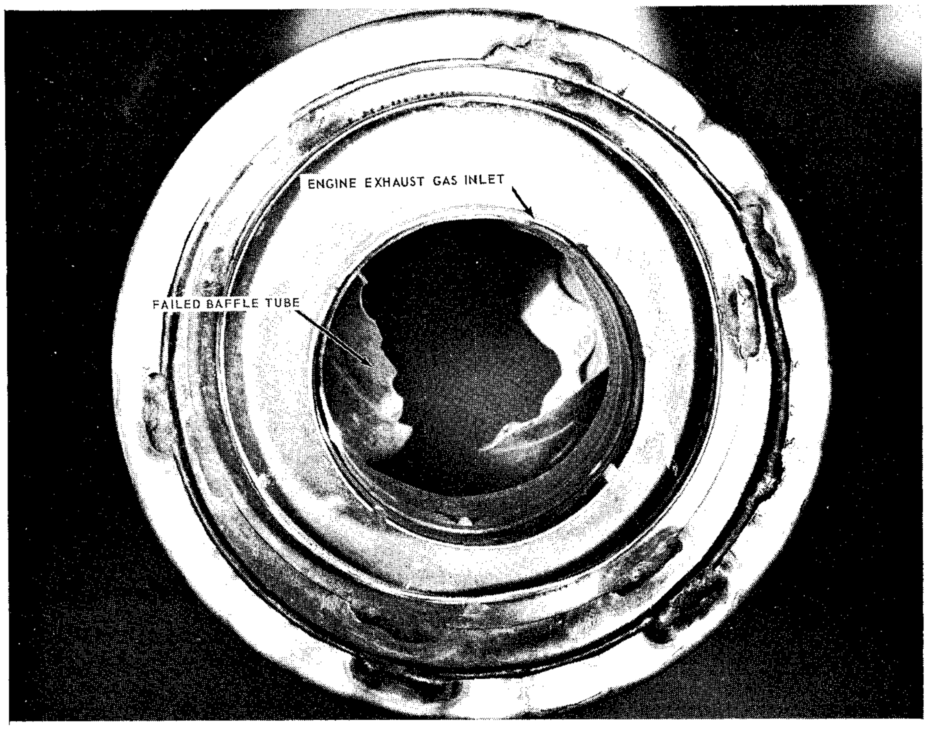


FIG. 1.5 FAILED MUFFLER BAFFLE TUBE

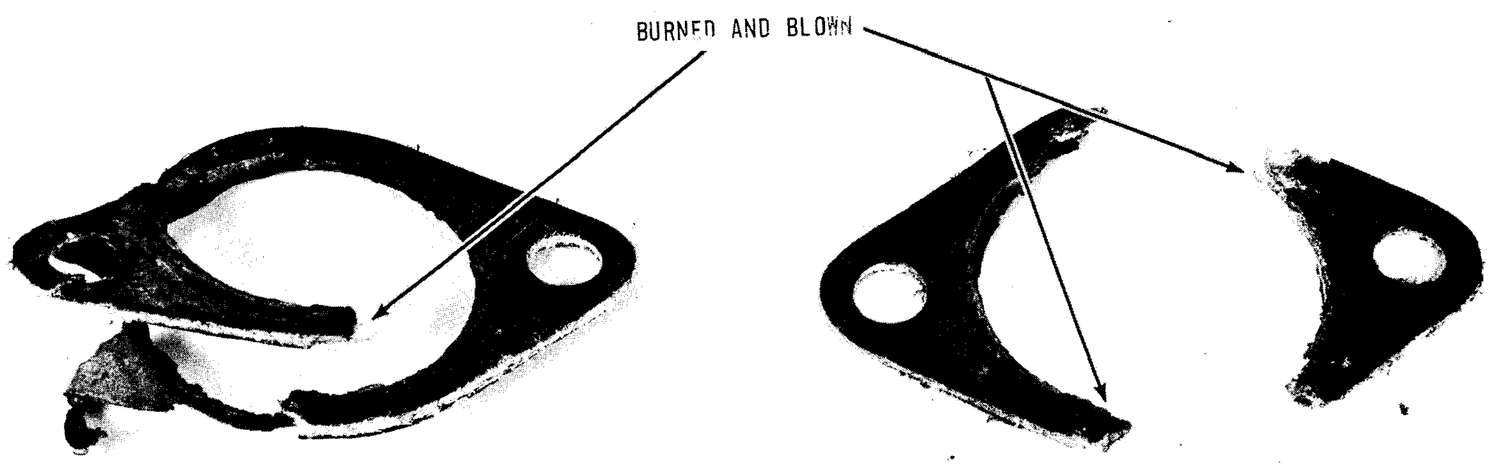


FIG. 1.6 FAILED ENGINE EXHAUST FLANGE GASKETS

Test Hours - 440: A fracture occurred in a muffler diffuser cone as depicted in Figure 1.7. The part was fabricated from AISI 321 stainless steel .050 inch thick. Metallurgical evaluation of this part is located under the subheadings of Samples Nos. 10 and 11, and the part is shown in Figures 41 through 45 of Reference 5. As stated, "All of the cones were heavily oxidized on the lower surface. The failed cone showed little, if any, evidence of oxidation on the upper surface. Examination of the microstructure revealed a substantial amount of sigma phase in the grain boundaries and some within the grains." It was determined from Reference 4 that this part operates under maximum temperature levels of 1500°F to 1600°F.

Test Hours - 448: A crack occurred along the radius of a muffler end plate at 448 test hours as shown in Figure 1.8. Three of four rivets joining the baffle tube to the end plate intake tube were completely sheared and the fourth, while still intact, was cracked and weakened by loss of material. This is shown in Figure 1.9. Metallographic examination is discussed under the subheading of Sample No. 7, and the defects are shown including the rivet failure in Figures 26 through 28 of Reference 5. Material was AISI 347 stainless steel. The baffle tube operated at temperature levels of 1500°F to 1600°F maximum, and the end plate operated at 1000°F to 1200°F maximum temperature, as determined in Reference 4.

Test Hours - 490: The clamp lock pin failed permitting the right manifold to separate from the muffler joint at 490 test hours. Exhaust gases were blasted through the existing openings under the cabin heater air shroud resulting in .065 percent carbon monoxide contamination of the cabin air. This malfunction is presented in Figures 1.10 and 1.11. Metal expansion with high-temperature exhaust gases may have influenced this failure. A number of similar failures has occurred in operating aircraft. The failure demonstrates and emphasizes that the cabin heaters must be designed and fabricated airtight or sealed to prevent outside contamination from entering the heaters upon occurrence of an unforseen failure. A section of the muffler including the joint was analyzed metallurgically under the subheading of Sample No. 6, and depicted in Figures 24, 25, and 26 of Reference 5. The material is AISI 347 stainless steel .030 inch thick in the joint area and the baffle tube is .020 inch thick. Maximum operational temperature of the joint was 1000°F to 1200°F and the baffle tube operated at 1500°F to 1600°F maximum. (See Reference 4.)

Test Hours - 550: A crack developed in the muffler outer wall heat exchanger surface at 550 test hours and contaminated the cabin air with .012 percent carbon monoxide. The defect is shown in Figure 1.12. A long history of both identical failures and general failures of this type have occurred in operating aircraft. The crack occurred in the radius of the stack inlet attachment, an area of stress concentration.

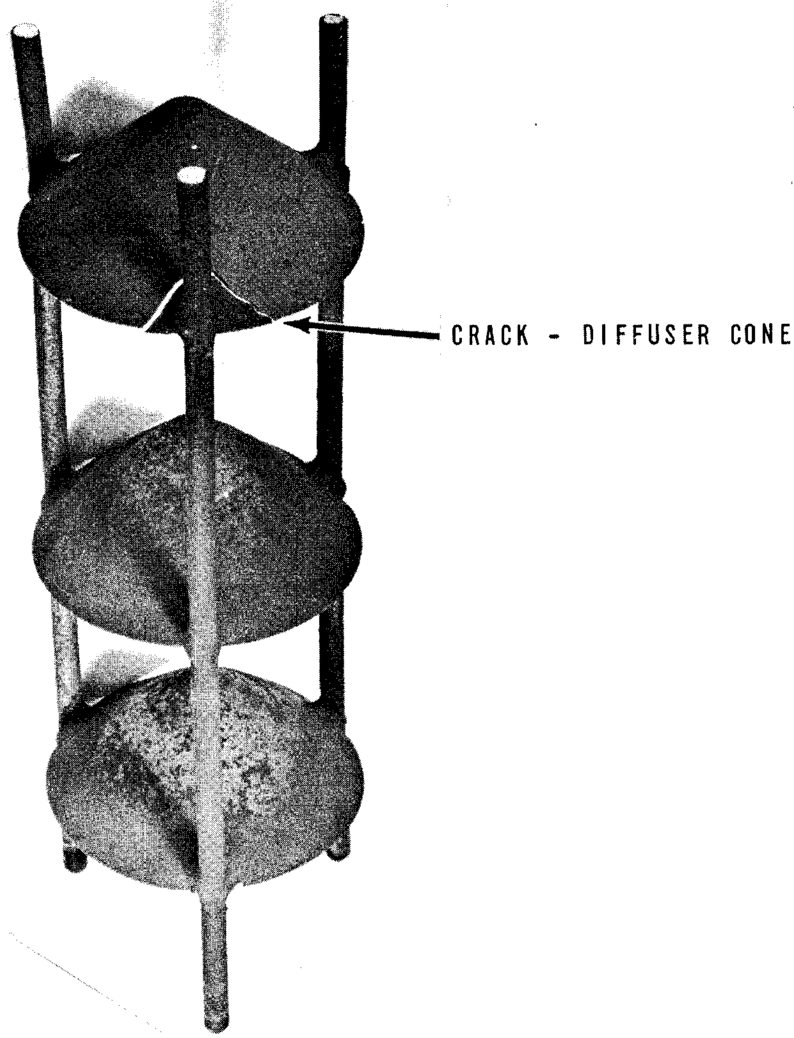


FIG. 1.7 FAILED MUFFLER DIFFUSER CONE

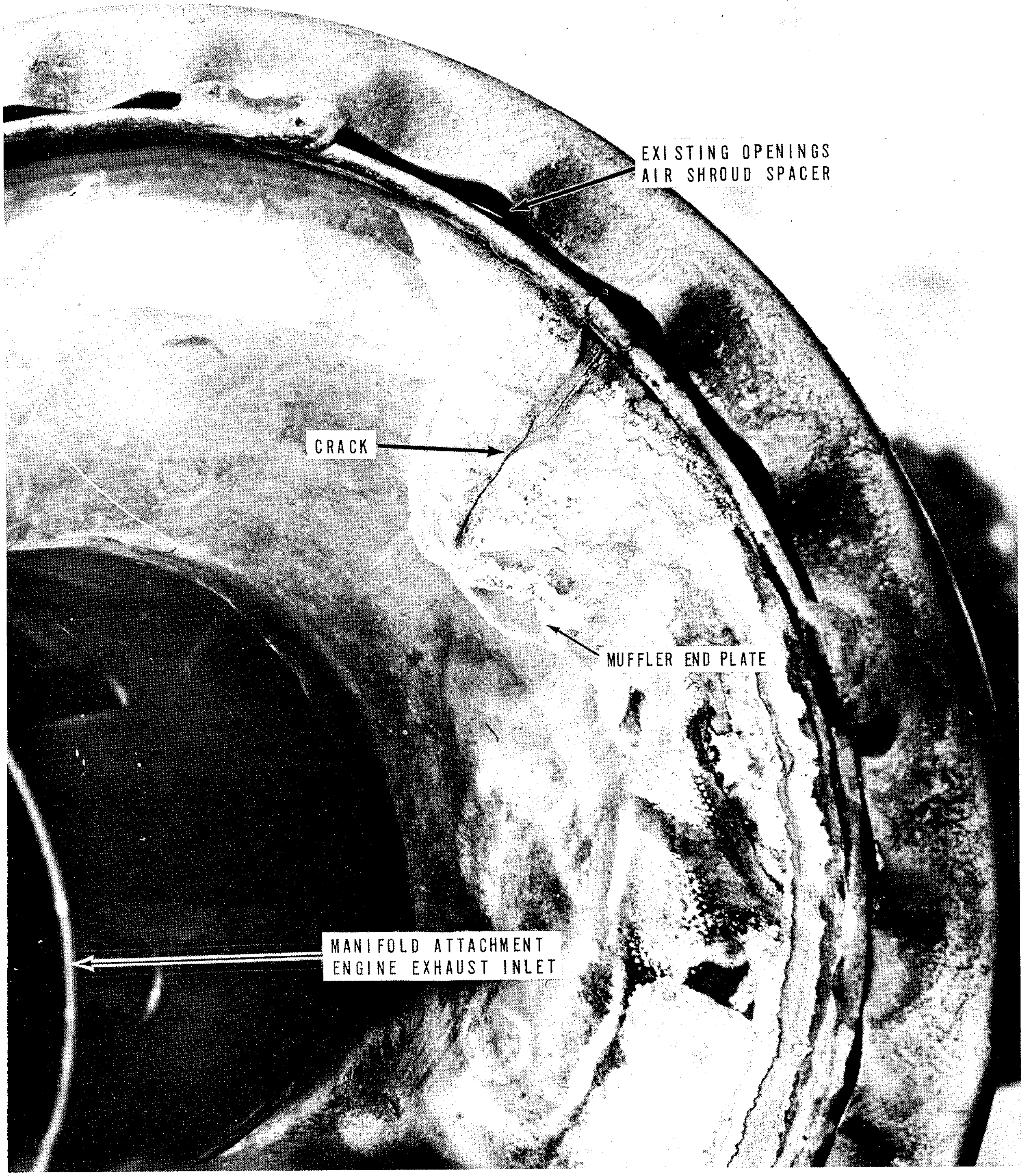


FIG. 1.8 FAILED MUFFLER END PLATE

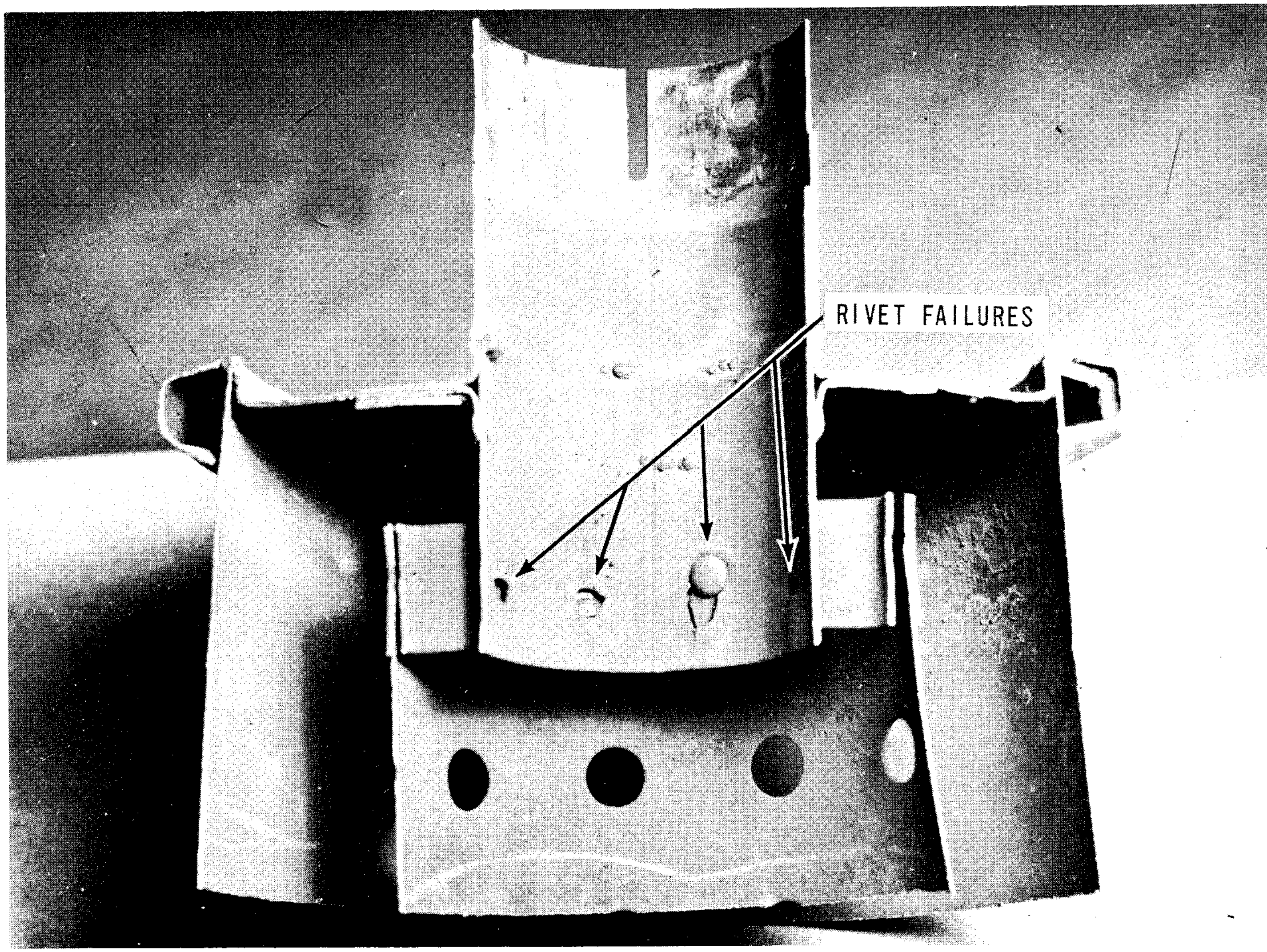
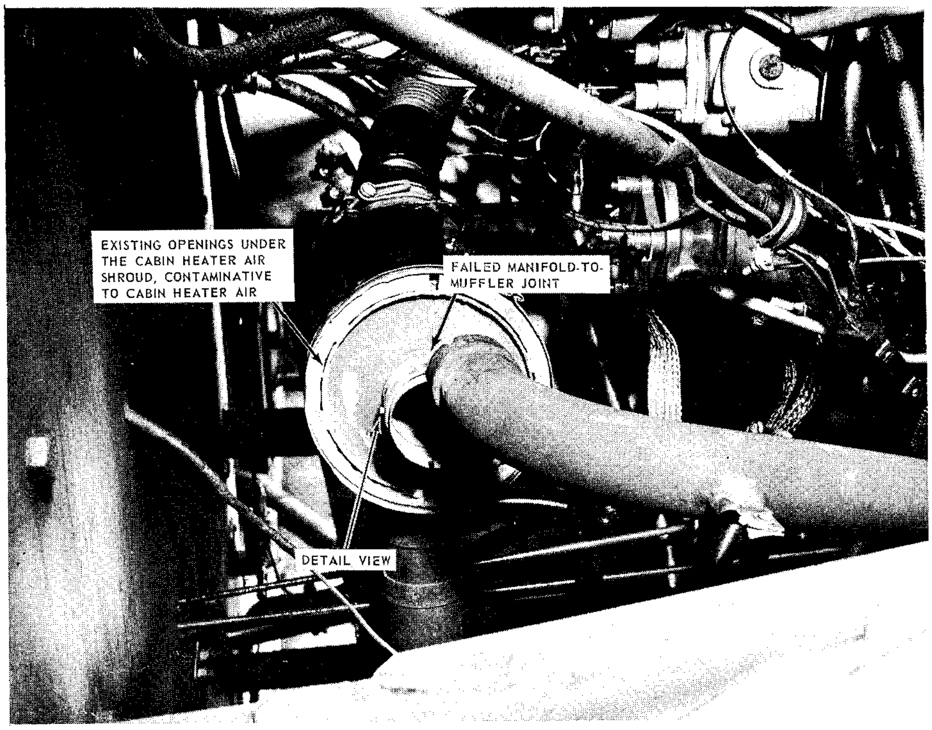


FIG. 1.9 FAILED BAFFLE TUBE RIVETS, MUFFLER



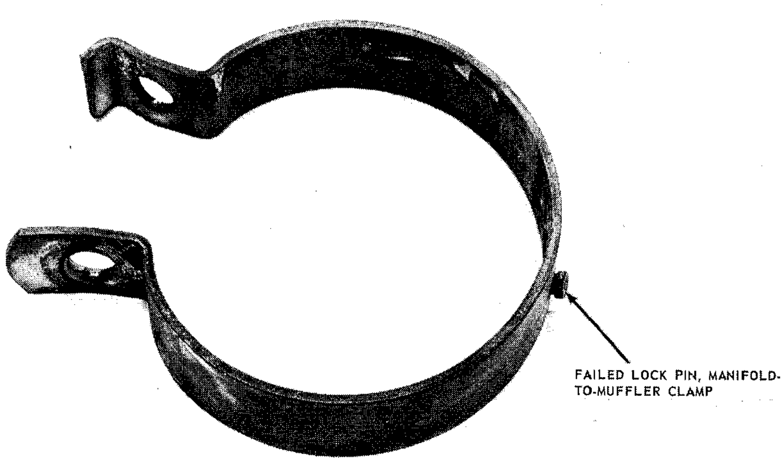
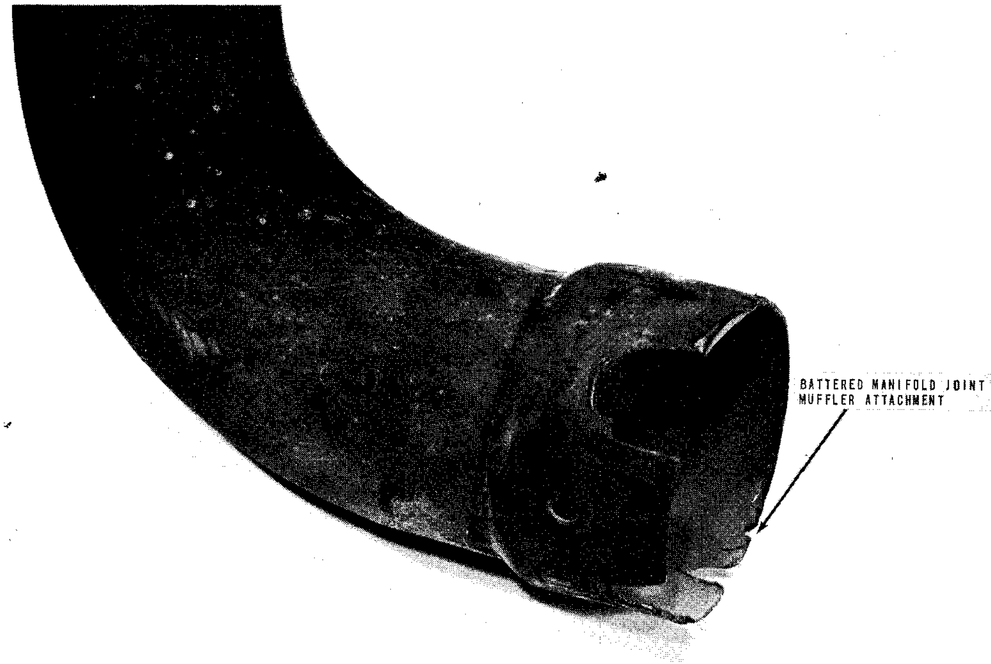


FIG. 1.10 FAILED MANIFOLD-TO-MUFFLER JOINT



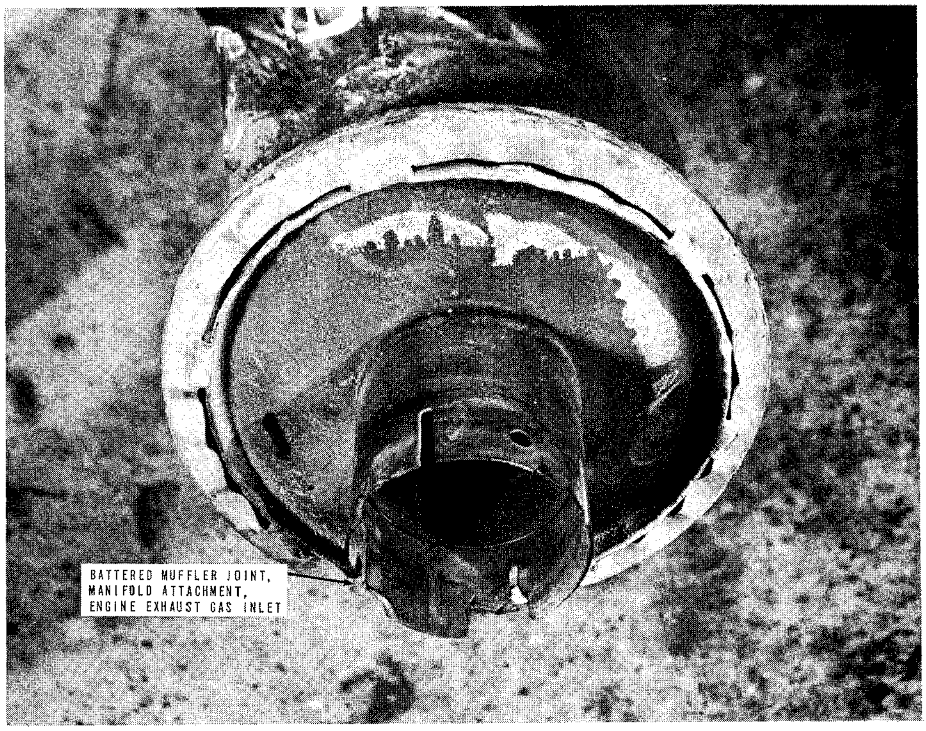
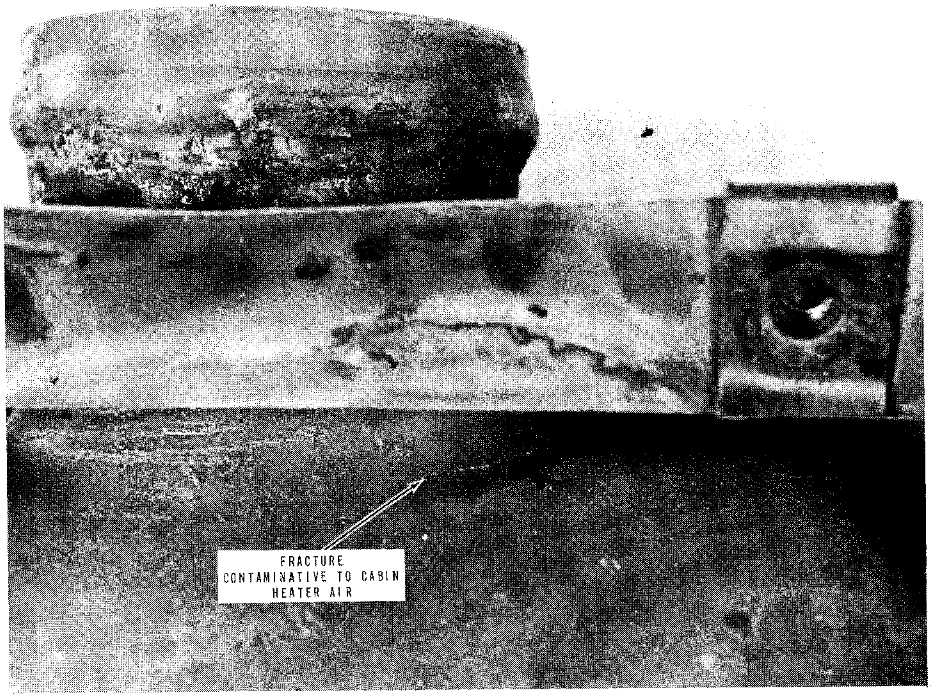


FIG. 1.11 BATTERED MUFFLER AND MANIFOLD JOINT

The material was AISI 321 stainless steel .030 inch thick operating under metal temperatures of 1000°F and 1200°F maximum on the outer surface. The inner surface was in contact with exhaust gases at maximum temperatures of 1380°F to 1480°F. (See Reference 4.)

Metallurgical evaluation is discussed under the subheading of Sample No. 9, and photomicrographs are shown in Figures 37 through 40 of Reference 5. As stated, "The sample was heavily oxidized on both the inside and outside surfaces. The outside surface showed deeper penetration at various locations along the surface. It is considered significant that the oxidation corrosion penetrates in some areas in a sharp pointed manner, thus creating points of stress concentration from which fatigue cracks can originate. The structure around the crack contained sigma phase distributed discontinuously in the grain boundaries, and severe oxidation."

Test Hours - 600: An exhaust system fabricated of a material consisting of 32 percent nickel, 46 percent iron, and 21 percent chromium was tested for 600 hours without failure. This material had been recommended in Reference 2 for those exhaust system components exposed to high temperatures and the products of combustion, particularly lead compounds. The exhaust system was fabricated of material stock .050 inch thick and conveyed exhaust gases at temperatures of 1500°F to 1600°F most likely resulting in diffuser cone metal temperatures of the same magnitude. Stack and muffler outer wall metal temperatures were operating at levels of 1000°F to 1200°F maximum. (See Reference 4.) Metallurgical analysis is contained under subheadings of Samples Nos. 14 through 17, and the material is depicted in Figures 50 through 59 of Reference 5. As stated, "The parts were free from failure and visual examination revealed no evidence of oxidation. The microphotographs of the samples in the unetched condition showed very little oxidation. Many titanium cyanonitrides were evident." In regard to the muffler wall, there was a conspicuous absence of oxidation. Specimens from the exhaust system fabricated of the nickel-iron-chromium alloy were compared metallurgically with identical specimens from the exhaust system fabricated of AISI 321 stainless steel. Both systems were tested for 600 hours on an engine rated at 260 hp with a compression ratio of 8.6:1. The metallurgical condition of the comparative specimens (AISI 321 stainless steel) is discussed under the subheadings of Samples Nos. 10 through 13, and shown in Figures 41 through 49 of Reference 5. The AISI 321 samples were heavily oxidized while the nickel-iron-chromium samples showed very little oxidation. Furthermore, over 600 test hours with three failures (112, 140, and 440 test hours) occurred in the exhaust system fabricated of AISI 321 stainless steel, while not any failures occurred in the exhaust system fabricated from the more corrosion-resistant nickel-iron-chromium alloy.



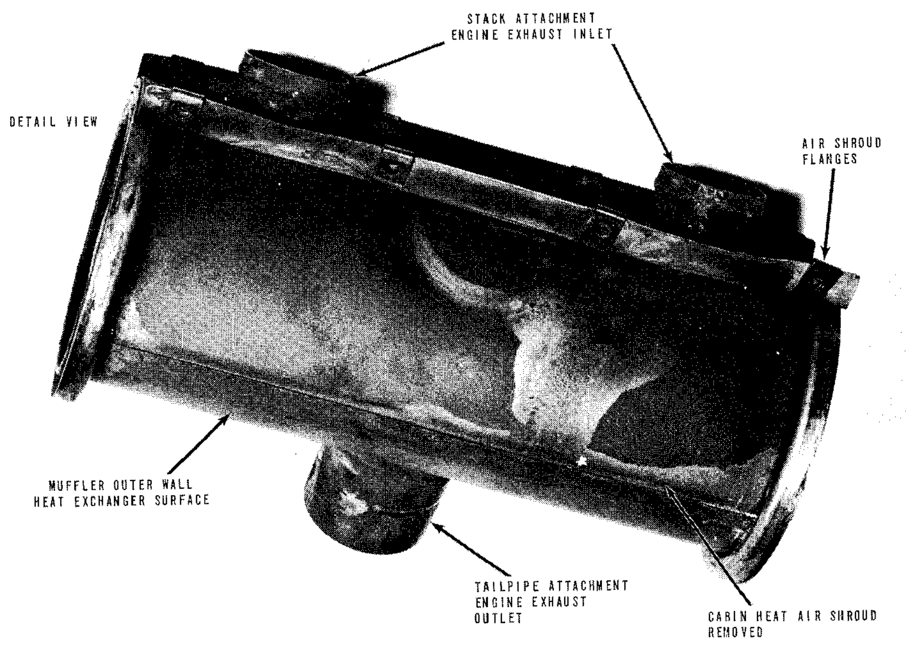


FIG. 1.12 FAILED CABIN HEAT EXCHANGER